Performance Analysis of Multi-hop Relay Cooperative Spectrum Sensing

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Abstract—**This paper analyzed the performance of multi-hop relay cooperative spectrum sensing. The closed form expression of the upper bound of the detection probability of multi-hop relay cooperation is derived in Rayleigh flat fading channel. It provides the theoretical basis for analyzing the performance of multi-hop relay cooperative spectrum sensing. Simulation results show that the detection probability decreases as the increase of the hop number when each hop sub-channel has the same average signal to noise ratio (SNR). The detection performance of three-hop relay cooperative spectrum sensing outperforms that of two-hop relay when both SNRs of the last two hops in three-hop relay are 3 dB bigger than the SNR of the second hop in two-hop relay.**

Index Terms—**cognitive radio, cooperative spectrum sensing, multi-hop relay, detection probability**

I. Introduction

With the rapid development of wireless communicate-on technologies and the increase of wireless communica-tion applications, the demand of spectrum has be on the increase. It resulted in the available spectrum resources becoming increasingly scarce. The conventional fixed spectrum allocation policy often leads to the low utilization of the licensed bands which forms an apparent contradiction with the increasingly scarce spectrum resources [1]. Cognitive radio is an intelligent spectrum sharing technology which is able to resolve the contradiction [2]. It allows the cognitive user to access the idle licensed bands opportunistically so as to reuse the spectrum resources and improve the spectrum utilization efficiency.

Spectrum sensing technology is the premise and basis of the realization of cognitive radio. Among single user spectrum sensing, the matched filter detection [3], energy detection [4] and cyclostationary feature detection [5] are the three main techniques. However, the performance of single user spectrum sensing deteriorates in the fading channel due to the effect of multipath fading and shadowing. In [6], a two-user network is considered, and the detection time is reduced and the overall agility is increased by cooperating. A practical algorithm, which allows cooperation between cognitive users, was studied and the benefit of cooperation in cognitive radio networks was illustrated in [7]. A cooperative spectrum sensing scheme, which minimizes the false alarm probability while satisfies the detection probability at a desired level, is proposed [8]. This scheme optimally combines the binary local sensing results with different combining weights and finally makes a global decision at the fusion center. In [9], a cooperative spectrum sensing scheme based on the best relay selection in multiple cognitive user networks is proposed. It improves the spectrum sensing performance by achieving the spatial diversity gain. Atapattu, Tellambura and Jiang Hai focused on data fusion and decision fusion and derived the upper bound for the average detection probability when all the relay users participate in cooperation in Rayleigh flat fading channel [10].

But most of all discussed the performance under two-hop relay. In two-hop relay network, however, when the channel condition between the relay user and the cognitive user are bad, the detection performance of two-hop relay cooperation may be deteriorated. Under this condition, the signal can be transmitted to the next relay, and then forwarded to the cognitive user. If the channel condition between the second relay user and the cognitive user is bad too, we may make use of the third and the fourth even more relay users to retransmit the primary signal. Thereby, we could obtain ideal spectrum sensing performance with multi-hop relay cooperative spectrum sensing. This paper mainly analyses the performance of multi-hop relay cooperative spectrum sensing. The closed form expression of the upper bound for the detection probability of multi-hop relay cooperation is derived in Rayleigh flat fading channel, which could provide the theoretical basis for the performance analysis.

II. Multi-hop Cognitive Network

A multi-hop relay cooperative spectrum sensing network is showed in Fig. 1. When the condition of the

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direct channel between the primary user and the cognitive user is bad, relay user is required to forward the primary signal to the cognitive user. In two-hop relay network, when there are obstacles between the relay user and the cognitive user, the received signal of the cognitive user from the relay user is weak, which requires the first relay user to transmit the primary signal to the second relay user, then the second relay transmit the signal to the cognitive user. If the channel condition between the second relay user and the cognitive user is bad too, the third or even more relay users are required to retransmit the primary signal.

Fig. 2 shows the diagram of multi-hop relay network. R_i (i=1,…,L) is the ith relay, α_i is the corresponding amplification factor, h_l, n_l (l=1,…,L+1) are the channel gain and additive white Gaussian noise (AWGN) of the lth hop sub-channel respectively, and h_0, n_0 are the channel gain and AWGN of the direct channel respectively. We assume that each hop sub-channel and the direct channel are independent each other, and all the channels are Rayleigh flat fading. The primary signal is assumed to be x, and each relay employs the amplify and forward (AF) protocol to transmit the received signal to the next relay. Therefore the signal received by the cognitive user from the multi-hop relay channel can be expressed as

$$y_{L+1} = \prod_{i=1}^{L}(\alpha_i h_i)h_{L+1}x + \sum_{i=1}^{L}\left(\prod_{k=i}^{L}\alpha_k h_{k+1}\right)n_i + n_{L+1} . \tag{1}$$

III. Performance Analysis of Spectrum Sensing

A. Energy Detection in AWGN Channel

In energy detection, the received signal is pre-filtered firstly by an ideal bandpass filter with bandwidth W, and the output of the filter is then squared and integrated over the detection time interval T to produce a energy test statistic Λ. The energy test statistic Λ is compared with a predefined threshold λ. The detection probability P_d and the false alarm probability P_f are represent as

$$P_d = \Pr(\Lambda > \lambda \mid H_1) = Q_u(\sqrt{2\gamma}, \sqrt{\lambda}), \tag{2}$$

$$P_f = \Pr(\Lambda > \lambda \mid H_0) = \frac{\Gamma(u, \frac{\lambda}{2})}{\Gamma(u)}, \tag{3}$$

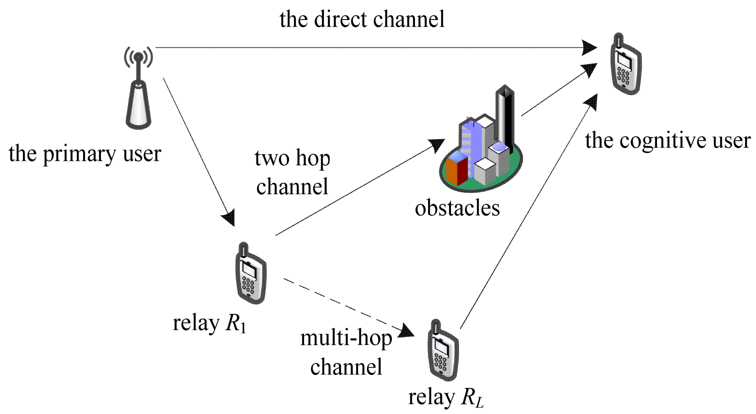


Figure 1. Multi-hop relay network

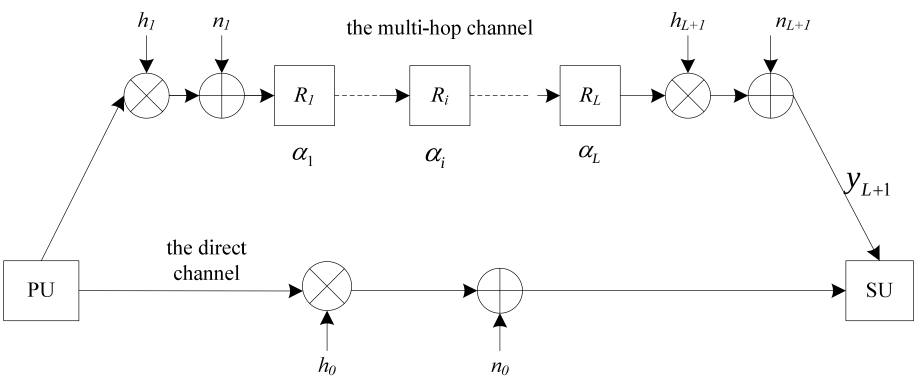


Figure 2. Diagram of multi-hop relay network.

where H_1 is the hypothesis that a primary user is active and H_0 indicates a primary user is absent, $u=TW$, γ is the signal to noise ratio (SNR) of the received signal, $Q_u(\cdot,\cdot)$ is the u order generalized Marcum-Q function, $\Gamma(\cdot)$ is the gamma function, and $\Gamma(\cdot,\cdot)$ is the upper incomplete gamma function. It is obvious that the false alarm probability P_f is independent of SNR of the signal received. We discuss mainly the detection probability P_d following.

B. Performance of Multi-hop Relay Cooperative Spectrum Sensing in Rayleigh Channel

The generalized Marcum-Q function can be written as a circular contour integral within the contour radius $r \in [0,1)$. Therefore, (2) can be re-written as [11]

$$P_d = \frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Omega}\frac{e^{(\frac{1}{z}-1)\gamma+\frac{\lambda}{2}z}}{z^u(1-z)}dz\,, \tag{4}$$

where Ω is a circular contour of radius $r \in [0,1)$. In Rayleigh fading channel, the SNR of signal received changes randomly. Therefore, the detection probability P_d is random and the average detection probability $\overline{P_d}$ is given by

$$\overline{P_d} = \frac{e^{-\frac{\lambda}{2}}}{j2\pi}\oint_{\Omega} g(z)dz\,, \tag{5}$$

and

$$g(z) = M_\gamma(\frac{1}{z}-1)\frac{e^{\frac{\lambda}{2}z}}{z^u(1-z)}\,. \tag{6}$$

$M_\gamma(s) = \mathrm{E}(e^{s\gamma})$ is the moment generating function (MGF) of SNR γ. Where $\mathrm{E}(\cdot)$ means expectation.

- **Consider the multi-hop channel only**

When the direct channel between the primary user and the cognitive user is bad, we take the multi-hop channel into consideration only. The SNR of signal received in the multi-hop relay channel can be written as

$$\gamma_{hop} = \frac{\prod_{i=1}^{L}|\alpha_i h_i|^2 |h_{L+1}|^2 E_p}{\sum_{i=1}^{L}\left(\prod_{k=i}^{L}|\alpha_k h_{k+1}|^2\right)N_i + N_{L+1}}\,, \tag{7}$$

where E_p is the signal power of the primary user, and N_i is the noise power of each hop sub-channel.

In order to satisfy the transmit power constraint of relay and form a optimal receiver, we employ the amplification factor of relay user to compensate the fading of the previous sub-channel, i.e., $\alpha_i h_i = 1$. Therefore, (7) is rewritten as

$$\gamma_{hop} = \frac{|h_{L+1}|^2 E_p}{\sum_{i=1}^{L}\left|\frac{h_{L+1}}{h_i}\right|^2 N_i + N_{L+1}} = \left[\sum_{i=1}^{L+1}\frac{1}{\gamma_i}\right]^{-1}\,, \tag{8}$$

where $\gamma_i = \frac{|h_i|^2 E_p}{N_i}$ is the instantaneous SNR of each hop sub-channel. γ_i has an exponential distribution and its probability density function (PDF) is given by

$$f_{\gamma_i}(\gamma) = \frac{1}{\overline{\gamma_i}}e^{-\frac{\gamma}{\overline{\gamma_i}}}\,, \tag{9}$$

where $\overline{\gamma_i}$ is the average SNR of each hop sub-channel.

It can be seen from (8) that $\gamma_{hop} < \min(\gamma_1,\gamma_2,\cdots,\gamma_{L+1})$. We make $\gamma_m = \min(\gamma_1,\gamma_2,\cdots,\gamma_{L+1})$, then $\gamma_{hop} < \gamma_m$. If we find the detection probability when the SNR is γ_m, we would get the upper bound of the detection probability when the SNR is γ_{hop}. We take this upper bound as the approximate value of the detection probability when the SNR is γ_{hop}. According to the probability theory, the distribution function of γ_m is

$$F_{\gamma_m}(\gamma) = 1-\prod_{i=1}^{L+1}(1-F_{\gamma_i}(\gamma)) = 1-e^{-\frac{\gamma}{\overline{\gamma_1}}}e^{-\frac{\gamma}{\overline{\gamma_2}}}\cdots e^{-\frac{\gamma}{\overline{\gamma_{L+1}}}}\,, \tag{10}$$

where $F_{\gamma_i}(\gamma)$ is the cumulative distribution function (CDF) of γ_i,

$$F_{\gamma_i}(\gamma) = \int_0^{\gamma} f_{\gamma_i}(\gamma)d\gamma = 1-e^{-\frac{\gamma}{\overline{\gamma_i}}}\,, \tag{11}$$

and the PDF of γ_m is given by

$$f_{\gamma_m}(\gamma) = \sum_{i=1}^{L+1} f_{\gamma_i}(\gamma)\prod_{\substack{k=1\\k\neq i}}^{L+1}(1-F_{\gamma_k}(\gamma)) = (\frac{1}{\overline{\gamma_1}}+\frac{1}{\overline{\gamma_2}}+\cdots+\frac{1}{\overline{\gamma_{L+1}}})e^{-(\frac{1}{\overline{\gamma_1}}+\frac{1}{\overline{\gamma_2}}+\cdots+\frac{1}{\overline{\gamma_{L+1}}})\gamma}\,. \tag{12}$$

Then, we can obtain the MGF of γ_m as

$$M_{\gamma_m}(s) = \int_0^\infty f_{\gamma_m}(\gamma) e^{s\gamma} d\gamma = A\frac{1}{A-s}, \quad (13)$$

where $A = (\frac{1}{\overline{\gamma_1}} + \frac{1}{\overline{\gamma_2}} + \cdots + \frac{1}{\overline{\gamma_{L+1}}})$.

In this case, $g(z)$ in (5) can be written as

$$g(z) = \frac{e^{\frac{\lambda}{2}z} A}{z^{u-1}(1-z)(1+A)(z-\Delta)}, \quad (14)$$

where $\Delta = \frac{1}{1+A}$.

We consider two cases: 1) when $u > 1$, there are $u-1$ poles at the origin and one pole at Δ in radius $r \in [0,1)$, and 2) when $u \le 1$, there is only one pole at Δ in radius $r \in [0,1)$. Therefore, an upper bound of $\overline{p_d}$, denoted $\overline{P_d^{up}}$, can be derived as

$$\overline{P_d^{up}} = \begin{cases} e^{-\frac{\lambda}{2}}(\mathrm{Re}\,s(g;0) + \mathrm{Re}\,s(g;\Delta)) : u > 1 \\ e^{-\frac{\lambda}{2}}\mathrm{Re}\,s(g;\Delta) : u \le 1 \end{cases}, \quad (15)$$

where $\mathrm{Re}\,s(g;0)$ and $\mathrm{Re}\,s(g;\Delta)$ denote the residue of the function $g(z)$ at the origin and Δ respectively

$$\mathrm{Re}\,s(g;0) = \frac{D^{u-2}\left(\frac{e^{\frac{\lambda}{2}z} A}{(1-z)(1+A)(z-\Delta)}\right)\Bigg|_{z=0}}{(u-2)!} \quad (16)$$

$$\mathrm{Re}\,s(g;\Delta) = \frac{e^{\frac{\lambda}{2}\Delta} A}{\Delta^{u-1}(1-\Delta)(1+A)} \quad (17)$$

where $D^n(f(z))$ is the nth derivative of $f(z)$ with respect to z.

- **Incorporation with the direct channel**

In above section, the cognitive user receives only signal from the multi-hop relay channel. If the cognitive user is close to the primary user, the direct channel would have some influence on the detection performance.

The SNR of the direct channel $\gamma_0 = \frac{|h_0|^2 E_p}{N_0}$, which has an exponential distribution with parameter $\overline{\gamma_0}$. The total SNR at the cognitive user is $\gamma_{tot} = \gamma_0 + \gamma_{hop}$, and $\gamma_{tot} < \gamma_u = \gamma_0 + \gamma_m$ due to $\gamma_{hop} < \gamma_m$. As discussed above, we take the detection probability of the case, in which the SNR is γ_u, as the approximate value of the detection probability when the SNR is γ_{tot}. Because γ_0 and γ_m are independent, the MGF of γ_u is

$$M_{\gamma_u}(s) = M_{\gamma_0}(s) M_{\gamma_m}(s), \quad (18)$$

where $M_{\gamma_0}(s)$ is MGF of γ_0

$$M_{\gamma_0}(s) = \int_0^\infty \frac{1}{\overline{\gamma_0}} e^{-\frac{\gamma}{\overline{\gamma_0}}} e^{s\gamma} d\gamma = \frac{1}{1-\overline{\gamma_0}s}. \quad (19)$$

According to (13) and (19), we get

$$M_{\gamma_u}(s) = M_{\gamma_0}(s) M_{\gamma_m}(s) = \frac{1}{1-\overline{\gamma_0}s}\frac{A}{A-s}. \quad (20)$$

In this case, $g(z)$ in (5) can be written as

$$g(z) = \frac{e^{\frac{\lambda}{2}z} A}{z^{u-2}(1-z)(1+\overline{\gamma_0})(z-\Delta_A)(1+A)(z-\Delta_B)}, \quad (21)$$

where $\Delta_A = \frac{\overline{\gamma_0}}{1+\overline{\gamma_0}}$ and $\Delta_B = \frac{1}{1+A}$.

We also consider two cases: 1) when $u > 2$, there are $u-2$ poles at the origin, one pole at Δ_A and one pole at Δ_B in radius $r \in [0,1)$, and 2) when $u \le 2$, there are one pole at Δ_A and one pole at Δ_B in radius $r \in [0,1)$. Therefore, $\overline{P_d^{up}}$ of this case can be derived as

$$\overline{P_d^{up}} = \begin{cases} e^{-\frac{\lambda}{2}}(\mathrm{Res}(g;0) + \mathrm{Res}(g;\Delta_A) + \mathrm{Res}(g;\Delta_B)) : & u > 2 \\ e^{-\frac{\lambda}{2}}(\mathrm{Res}(g;\Delta_A) + \mathrm{Res}(g;\Delta_B)) : & u \le 2 \end{cases} \quad (22)$$

where $\mathrm{Re}\,s(g;0)$, $\mathrm{Re}\,s(g;\Delta_A)$ and $\mathrm{Re}\,s(g;\Delta_B)$ denote the residue of the function $g(z)$ at the origin, Δ_A and Δ_B respectively,

$$\mathrm{Re}\,s(g;0) = \frac{D^{u-3}\left(\frac{e^{\frac{\lambda}{2}z} A}{(1-z)(1+\overline{\gamma_0})(z-\Delta_A)(1+A)(z-\Delta_B)}\right)\Bigg|_{z=0}}{(u-3)!} \quad (23)$$

$$\mathrm{Re}\,s(g;\Delta_A) = \frac{e^{\frac{\lambda}{2}\Delta_A} A}{\Delta_A^{\,u-2}(1-\Delta_A)(1+\overline{\gamma_0})(1+A)(\Delta_A-\Delta_B)} \quad (24)$$

$$\operatorname{Re}s(g;\Delta_B)=\frac{e^{\frac{\lambda}{2}\Delta_B}A}{\Delta_B^{\,u-2}(1-\Delta_B)(1+\overline{\gamma_0})(\Delta_B-\Delta_A)(1+A)} \tag{25}$$

According to (15) and (22), we can get the approximate value of the detection probability of multi-hop relay cooperative spectrum sensing under the two cases.

Ⅳ. NUMERICAL RESULTS

In this section, we provide some simulation results and analyze the performance of the cooperative spectrum sensing. For all the simulations, time bandwidth product u is set to be 10. we assume that the channels between any two users are independent and Rayleigh fading.

First, we consider the case where each hop sub-channel has the same average SNR. Fig. 3 illustrates the receiver operating characteristic (ROC) curves in the case of multi-hop relay channel when the average SNR is 5 dB. It is evident that the detection probability decreases with the increase of the number of hop when each hop sub-channel has the same average SNR. The performance in the case of two-hop relay is best.

Fig. 4 gives the ROC curves when the direct channel participates in cooperation. The average SNR of each hop sub-channel and the two direct channels are 5 dB, 0 dB and 3 dB respectively. From Fig. 4 (a), we can see that the multi-hop relay cooperative spectrum sensing improves the detection probability compared with non-cooperative spectrum sensing. But the detection probability decreases with the hop number increase. Compared Fig. 4 (a) with Fig. 3, we obtain that the direct channel participates in cooperation improves the detection probability largely. For example, when the false alarm probability is 0.2, the detection probability with the direct channel involved in cooperation is improved about 0.1 compared to ignore the direct channel. Fig. 4 (b) indicates that increasing the SNR of the direct channel can improve the detection probability of spectrum sensing.

Then, we take two-hop relay (L=1) and three-hop relay (L=2) into account. We analyze the detection performance of multi-hop relay cooperative spectrum sensing when each hop sub-channel has different average SNR.

Fig. 5 shows the ROC curves of two-hop relay and three-hop relay when the direct channel SNRs are 0 dB and 3 dB respectively. "L=1(8, 0)" means that in two-hop relay, the average SNR of first hop sub-channel is 8 dB and the one of second hop sub-channel is 0 dB; "L=2(8, 3, 3)" refers in three-hop relay, the average SNR of first hop sub-channel is 8 dB, the average SNRs of second hop sub-channel and third hop sub-channel are 3 dB. In Fig. 5 (a), when the SNRs of the last two hops in three-hop relay are 3 dB, it obtains the same detection performance with two-hop relay, and the detection probability gradually improves when the SNRs of the last two hops increase to 5 dB and 7 dB. In Fig. 5 (b), as the SNR of the direct channel increases to 3 dB, the detection probabilities of various cases have been greatly improved.

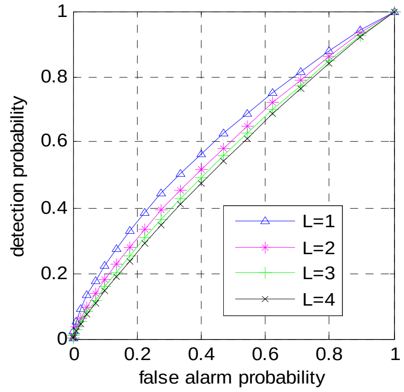
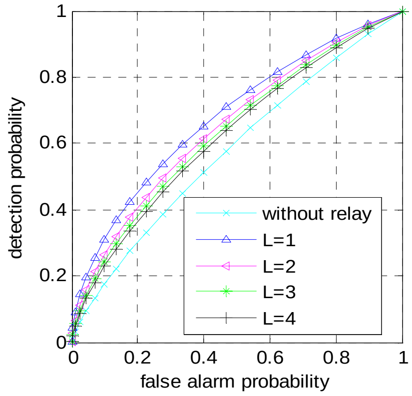
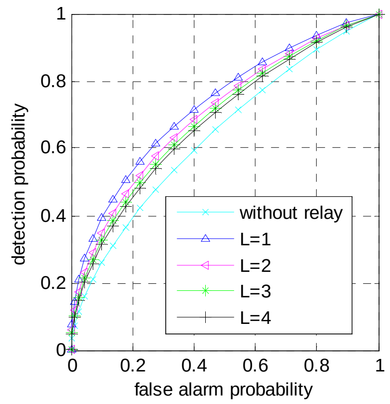


Figure 3 . ROC curves of considering the multi-hop channel only

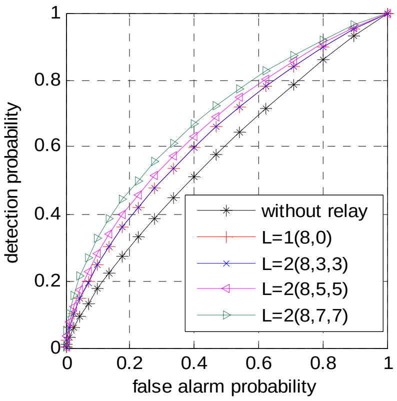


(a) $\overline{\gamma_0}$ =0 dB

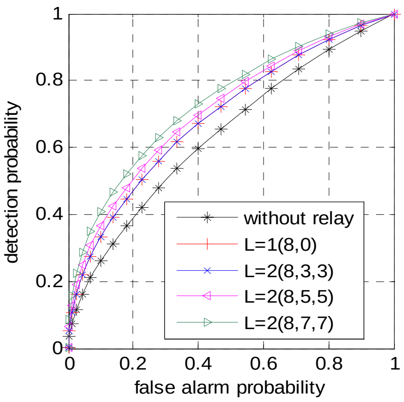


(b) $\overline{\gamma_0}$ =3 dB

Figure 4 . ROC curves of considering both the multi-hop channel and the direct channel

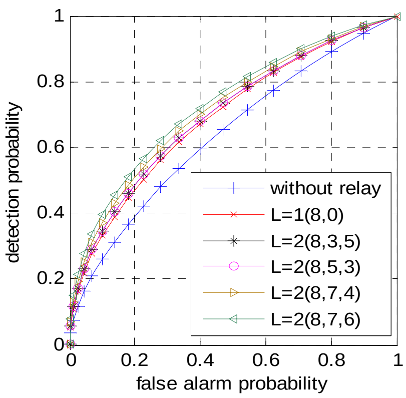


(a) $\overline{\gamma_0}$ =0 dB



(b) $\overline{\gamma_0}$ =3 dB

Figure 5. ROC curves of two hop relay and three hop relay cooperative spectrum sensing



(b) $\overline{\gamma_0}$ =3 dB

Figure 6. ROC curves of two hop relay and three hop relay cooperative spectrum sensing

The detection performance of cooperative spectrum sensing when each hop sub-channel in three-hop relay has different SNR is showed in Fig. 6. Among the SNRs of the last two hops in three-hop relay, one is equal to 3 dB and another is greater than 3 dB, or both are greater than 3 dB. It is obvious that the detection performance of three-hop relay cooperative spectrum sensing is better than that of two-hop relay, and the detection probabilities become higher as the SNRs of the last two hops increases. Fig. 6 (b) also illuminated that when the SNR of the direct channel increases to 3 dB, the detection performance is improved under various conditions.

In summary, the simulation results show that when each hop sub-channel in multi-hop relay with the same average SNR, the bigger the hop number, the lower the detection probability, and two-hop relay cooperation has the best detection performance. When each hop sub-channel has different average SNR and the channel conditions of two-hop relay is bad, the detection performance of three-hop relay outperforms that of two-hop relay.

V. Conclusions

This paper focuses on the performance in multi-hop relay cooperative spectrum sensing. The theoretical closed form expression of the upper bound for the detection probability of multi-hop relay cooperation is derived in Rayleigh flat fading channel. It would provide the theoretical basis for analyzing the performance of multi-hop relay cooperative spectrum sensing. Simulation results show that the detection probability decreases with the increase of the number of hop when each hop sub-channel with the same average SNR, and two-hop relay has the best performance. However, when the second hop in two-hop relay with bad channel condition, the detection performance of three-hop relay cooperative spectrum sensing outperforms that of two-hop relay cooperative spectrum sensing when SNRs of the last two hops in three-hop relay both 3 dB bigger than SNR of the second hop in two-hop relay.

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